TMCP–95–3
March 1995

# The GRACE system for SUSY processes

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**Abstract**

We introduce a new method to treat Majorana fermions on the GRACE system which has been developed for the automatic computation of the matrix elements for the processes of the standard model. In the GRACE system, we already have such particles as Dirac fermions, gauge bosons and scalar bosons within the standard model. On the other hand, in the SUSY models there are Majorana fermions. In the first instance, we have constructed a system for the automatic computation of cross-sections for the processes of the SUSY QED. The system has also been applied to another model including Majorana fermions, the minimal SUSY standard model (MSSM), by the re-definition of the model file.

# 1 Introduction

It has been a promising hypothesis that there exists a symmetry called supersymmetry (SUSY) between bosons and fermions at the unification-energy scale. It, however, is a broken symmetry at the electroweak-energy scale. The relic of SUSY is expected to remain as a rich spectrum of SUSY particles, partners of usual matter fermions, gauge bosons and Higgs scalars, named sfermions, gauginos and higgsinos, respectively [1].

The quest of these SUSY particles has already been one of the most important pursuits to the present high-energy physics [2]. Although such particles have not yet been discovered, masses of them are expected to be $O(10^2)$ GeV [3]. In order to obtain signatures of the SUSY-particle production, electron-positron colliding experiments are preferable because the electroweak interactions are clean and well-known. Thus we hope SUSY

particles will be found out at future TeV-region (sub-TeV region) $e^-e^+$-colliders such as CLIC, NLC and JLC [4].

For the simulations of the experiments, we have to calculate the cross-sections for the processes with the final 3-body or more. We have already known within the standard model that the calculation of the helicity amplitudes is more advantageous to such a case than that of the traces for the gamma matrices with REDUCE [5, 6]. The program package CHANEL [7] is one of the utilities for the numerical calculation of the helicity amplitudes.

It, however, is also hard work to construct a program with many subroutine calls of CHANEL by hand. Thus we need a more convenient way to carry out such a work. The GRACE system [8], which automatically generates the source code for CHANEL, is one of the solutions. The system also includes the interface and the library of CHANEL, and the multi-dimensional integration and event-generation package BASES/SPRING v5.1 [9].

In the SUSY models, there exist Majorana fermions as the neutral gauginos and higgsinos, which become the mixed states called neutralinos. Since anti-particles of Majorana fermions are themselves, there exists so-called 'Majorana-flip', the transition between particle and anti-particle. This has been the most important problem which we should solve when we realize the automatic system for computation of the SUSY processes.

In a recent work [10, 11], we developed an algorithm to treat Majorana fermions in CHANEL. In the standard model, we already have such particles as Dirac fermions, gauge bosons and scalar bosons in the GRACE system. Thus we can construct an automatic system for the computation of the SUSY processes by the algorithm above in the GRACE system. In this work, we present the check list of the system at this time, and one of the results.

# 2 Majorana fermions into new GRACE

In Fig. 1, we present the system flow of GRACE [12]. The GRACE system has become more flexible for the extension in the new version called '**grc**' [13], which includes a new graph-generation package. With this package, every graphs can be generated based on a user-defined model. It is necessary for us to make the interface and the library of CHANEL and the model file for including the SUSY particles.

The method of computation in the program package CHANEL is as follows:

1. To divide a helicity amplitude into vertex amplitudes.

2. To calculate each vertex amplitude numerically as a complex number.

3. To reconstruct of them with the polarization sum, and calculate the helicity amplitudes numerically.

The merit of this method is that the extension of the package is easy, and that each vertex can be defined only by the type of concerned particles.

Here we propose an algorithm [10, 11] for the implementation of the embedding Majorana fermions in CHANEL as follows:

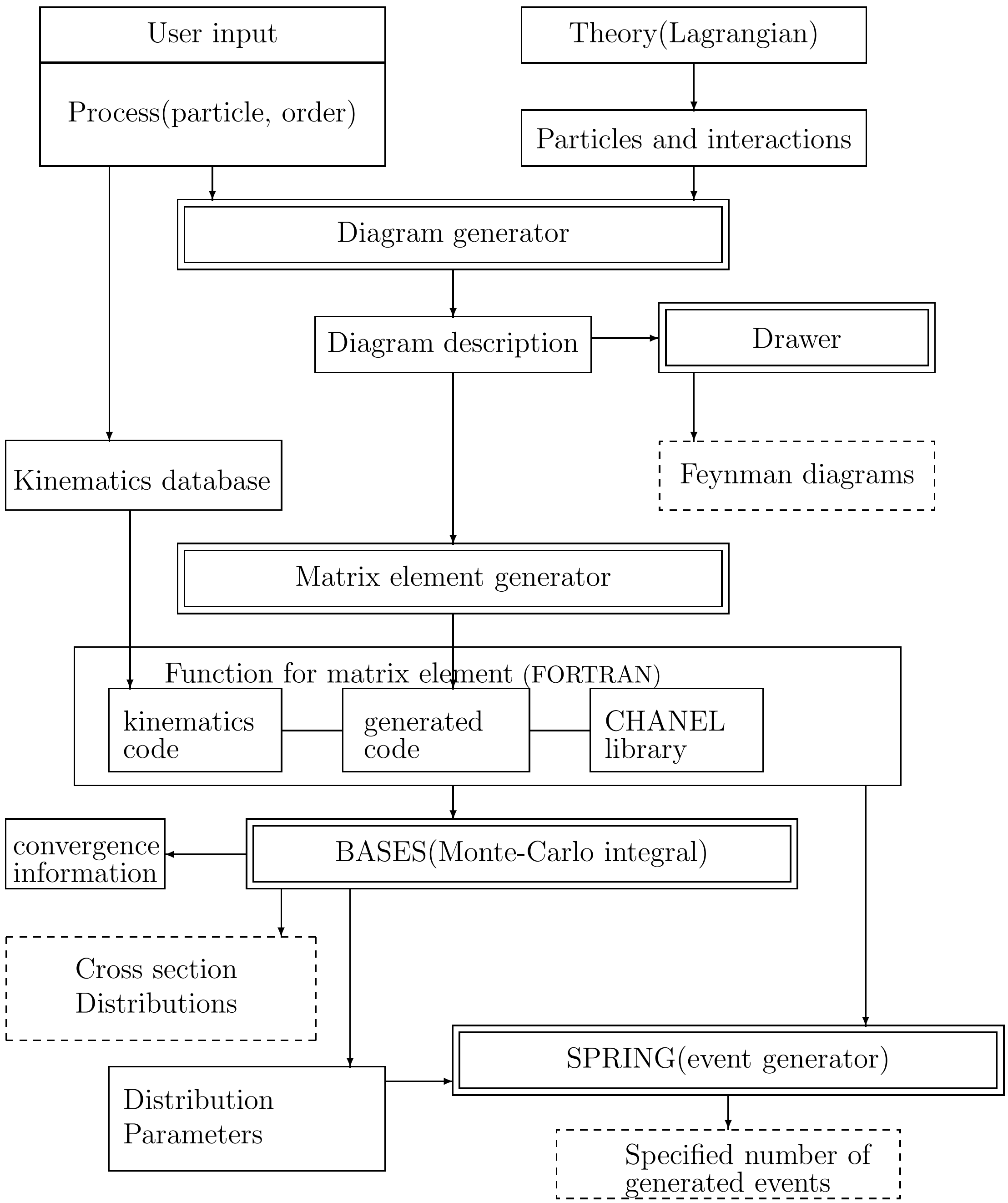


Fig. 1. GRACE system flow

- **policy**
  1. To calculate a helicity amplitude numerically.
  2. To replace each propagator by wave functions or polarization vectors, and calculate vertex amplitudes.
  3. **Not to** move charge-conjugation matrices.
- **method**
  1. To choose a direction on a fermion line.
  2. To put wave functions, vertices and propagators along the direction in such a way:
     i) To take the transpose for the reverse direction of fermions
     ii) To use the propagator with the charge-conjugation matrix for the Majorana-flipped one.

As a result, the kinds of the Dirac-Majorana-scalar vertices are limited to four types:

(1) $\overline{U}\Gamma U$

(2) $U^{\mathrm{T}}\Gamma\overline{U}^{\ \mathrm{T}}$

(3) $\overline{U}C^{\mathrm{T}}\Gamma^{\mathrm{T}}\overline{U}^{\ \mathrm{T}}$

(4) $U^{\mathrm{T}}\Gamma^{\mathrm{T}}C^{-1}U$

where $U$'s denote wave functions symbolically without their indices, and $C$ is the charge-conjugation matrix. The symbol $\Gamma$ stands for the scalar vertex such as

$$\Gamma = A_{\mathrm{L}} \cdot \frac{1-\gamma}{2} + A_{\mathrm{R}} \cdot \frac{1+\gamma}{2} \quad .$$

The vertices (2)$\sim$(3) are related to the vertex (1) which is the same as the Dirac-Dirac-scalar vertex in the subroutine of CHANEL. Thus we can build three new subroutines for the added vertices. We have performed the installation of the subroutines above with the interface on the new GRACE system.

# 3 Numerical results

At the start for the check of our system, we have written the model file of the SUSY QED. In this case, there is only one Majorana fermion, photino. Next we have extended the model file and the definition file of couplings for the MSSM. The tests have been performed by the exact calculations with the two methods, our system and REDUCE. In Table I, the tested processes are shown as a list. The references in the table (without [11]) are not the results of the tests, but for help.

Here we present the results for the single-selectron production within the SUSY QED process at the energy $\sqrt{s} = 190$ GeV. The masses of the concerned particles are $M_{\tilde{\gamma}} = 50$

| Process | | Number of diagrams | Comment | Check | Reference |
|---|---|---|---|---|---|
| **SUSY** | **QED** | | | | |
| $e^-e^- \to$ | $\tilde{e}_{\rm R}^-\tilde{e}_{\rm R}^-$ | 2 | Majorana-flip | OK | |
| | $\tilde{e}_{\rm L}^-\tilde{e}_{\rm L}^-$ | 2 | in internal lines | OK | [11] |
| | $\tilde{e}_{\rm R}^-\tilde{e}_{\rm L}^-$ | 2 | | OK | |
| $e^-e^+ \to$ | $\tilde{e}_{\rm R}^-\tilde{e}_{\rm R}^+$ | 2 | Including pair | OK | [14] |
| | $\tilde{e}_{\rm L}^-\tilde{e}_{\rm L}^+$ | 2 | annihilation | OK | [14] |
| $e^-e^+ \to$ | $\tilde{e}_{\rm R}^-\tilde{e}_{\rm L}^+$ | 1 | Values are | OK | [14] |
| | $\tilde{e}_{\rm R}^+\tilde{e}_{\rm L}^-$ | 1 | equal | OK | [14] |
| $e^-e^+ \to$ | $\tilde{\gamma}\tilde{\gamma}$ | 4 | F-B symmetric | OK | [11] |
| $e^-e^+ \to$ | $\tilde{\gamma}\tilde{\gamma}\gamma$ | 12 | Final 3-body | OK | [15] |
| $e^-e^+ \to$ | $\tilde{e}_{\rm R}^-\tilde{\gamma}e^+$ | 12 | Including every | OK | [16] |
| | | | elements for tests | | [17] |
| **MSSM** | | | | | |
| $e^-e^- \to$ | $\tilde{e}_{\rm L}^-\tilde{e}_{\rm L}^-$ | 8 | 4 Majorana fermions | OK | |
| $e^-e^+ \to$ | $\tilde{\chi}_1{}^-\tilde{\chi}_1{}^+$ | 3 | | OK | |

Table I. The list of the tested processes.

GeV, $M_{\tilde{e}_{\rm R}} = 100$ GeV and $M_{\tilde{e}_{\rm L}} = 130$ GeV in the calculation. This is the case that the pair-production processes occur for both selectrons at the JLC-I energy, but they do not at the LEP-II energy. The Feynman diagrams for this process, which are drawn by the program package '**gracefig**' [18] in the new GRACE, are shown in Fig. 2.

In Fig. 3, we show the angular distribution of the outgoing positron in the process $e^-e^+ \to \tilde{e}_{\rm R}^-\tilde{\gamma}e^+$. Here we use BASES for the calculation from the REDUCE output. The result is in beautiful agreement with the value that is obtained by GRACE at each bin of the histogram. Since the two diagrams with the one-photon exchange dominate in this case, there is a steep peak in the direction of the initial positron. In such a case, the equivalent-photon approximation (EPA) works well [17].

In Fig. 4, we show the $T_S$ distribution of the selectron in the process $e^-e^+ \to \tilde{e}_{\rm R}^-\tilde{\gamma}e^+$. The quantity $T_S$ is defined in Ref. [17] as

$$T_S = \frac{{P_T}^2 + {M_{\tilde{e}_{\rm R}}}^2}{{M_{\tilde{e}_{\rm R}}}^2} \quad ,$$

where $P_T$ denotes the transverse momentum of the selectron. We show also the $P_T$ distribution of the selectron in the process $e^-e^+ \to \tilde{e}_{\rm R}^-\tilde{\gamma}e^+$ in Fig. 5. Here we calculate the two dominant diagrams for comparison with the result from EPA.

# 4 Summary

We introduce a new method to treat Majorana fermions on the GRACE system for the automatic computation of the matrix elements for the processes of the SUSY models. In

the first instance, we have constructed the system for the processes of the SUSY QED because we should test our algorithm for the simplest case. The numerical results convince us that our algorithm is correct.

It is remarkable that our system is also applicable to another model including Majorana fermions (*e.g.* the MSSM) once the definition of the model file is given. We have calculated the processes $e^-e^+ \to \tilde{\gamma}\tilde{\gamma}\gamma$ and $e^-e^+ \to \tilde{e}_{\rm R}^-\tilde{\gamma}e^+$ within the SUSY QED. We should calculate the single-photon event from $e^-e^+ \to \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma$ [15], and the resultant single-positron (electron) event from the single-selectron production $e^-e^+ \to \tilde{e}^{\mp}\tilde{\chi}_1^0 e^{\pm}$ [16] as soon as possible. It should be emphasized that the GRACE system including SUSY particles is the powerful tool for this purpose.

# 5 Acknowledgements

This work was supported in part by the Ministry of Education, Science and Culture, Japan under Grant-in-Aid for International Scientific Research Program No.04044158. One of the author (M.J.) and Dr. H. Tanaka have been also indebted to the above-mentioned Ministry under Grant-in-Aid No.06640411.

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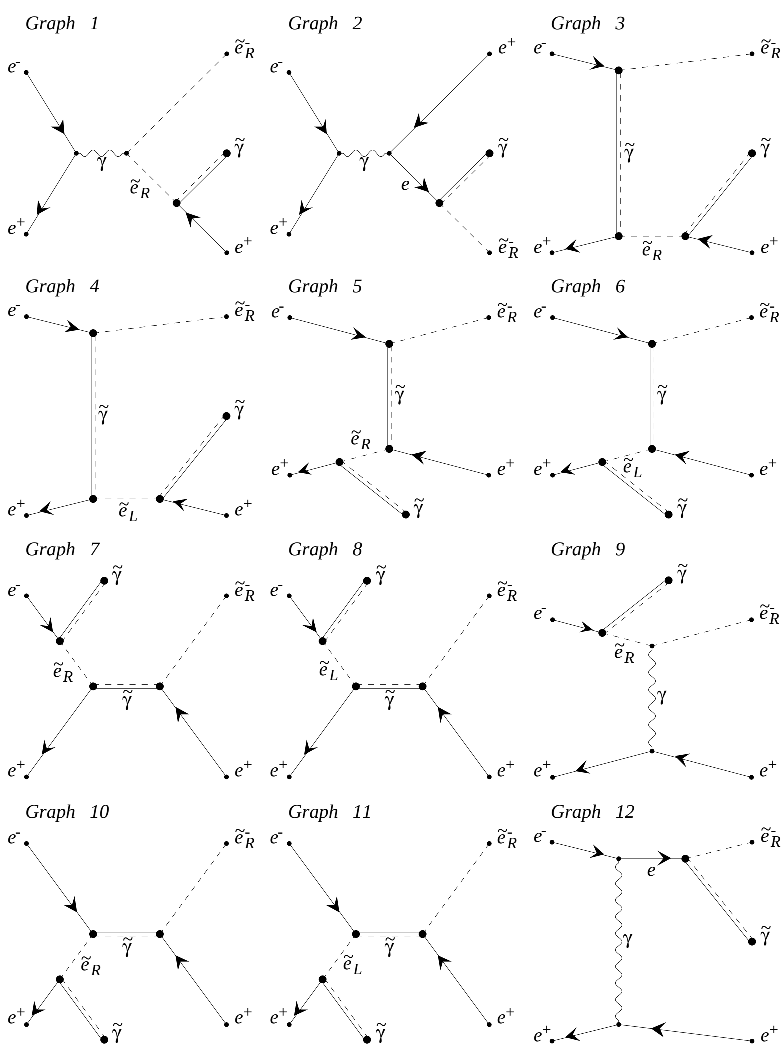


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